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XIAO NIE

SINR AND CHANNEL CAPACITY IN TERAHERTZ NETWORKS

MASTER OF SCIENCE THESIS

Examiner: prof. Dmitri Moltchanov
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ABSTRACT

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Terahertz technology is a new technology in communication networks compared with traditional network technology. Because of the limitations of generators and detectors for terahertz waves, the research on this bandwidth was quite limited. Considering the promising future of terahertz networks, it is necessary to research in this bandwidth. As the channel capacity is a crucial factor in estimating a network, relevant channel capacity of a given terahertz band will be calculated.

In this thesis, history of terahertz technology and the different applications of different frequencies in terahertz bandwidth are explained. In channel capacity calculation, important concepts SNR and SINR which are the key factors affecting channel capacity will be illustrated. Simulation model of the thesis which is based on Poisson Point Process is explained. Subsequently SINR and channel capacity of current environment will be calculated. By analyzing the results, the relevance of distance affection is deployed. Depending on the received results of SINR and channel capacity of a single node, CDF curves of both parameters will be plotted. Finally, the advantages and disadvantages of this thesis will be explained. The existing work of the thesis will explain what still need to be improved and researched in the future.

PREFACE

This Master thesis was written at Tampere University of Technology, Tampere, Finland during the period of January 2015 – May 2016.

This thesis is the integral part of my Master of Science program in Information Technology. For graduation process, this thesis has been concluded and presented to the Faculty of Computing and Electrical Engineering at Tampere University of Technology in Finland.

I am grateful to my supervisor Dmitri Moltchanov of Institute of Communication Engineering in Tampere University of Technology, for his valuable guidance which helps me and keep me on track during whole thesis period. He is always there for me when I need some help in both research and writing. And also I would like to thank all my professors and lecturers, who helped to acquire more insight in telecommunication and terahertz networks by presenting their great lectures and guidance during my Master's Programme.

Finally, I am gratitude to my friends and family for their precious support and encouragements during hard times throughout this period.

Tampere, 25.05.2016

Xiao Nie

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LIST OF SYMBOLS AND ABBREVIATIONS

BER	bit error rate
BWO	back wave oscillator
CDF	cumulative distribution function
CW	continuous wave
DB	decibel
DW	discrete wave
FEL	free electron laser
FIR	far-infrared
GB	gigabytes
ICs	integrated circuits
IoNT	Internet of Nano Things
IoT	Internet of things
IR	Infrared
LAN	local area network
MAX	maximum
MB	megabyte
Min	minimum
MIX	mixer
MMW	millimeter wave
MW	microwave
NEP	noise equivalent power
ORNL	oak ridge national laboratory
PC	photonic crystal

PDF	probability distribution function
REC	receiver
RF	radio frequency
Si	silicon
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
Submm	Sub-millimeter
TB	terabyte
THz	terahertz

1. INTRODUCTION

1.1 Terahertz network compared with traditional networks

The terahertz band is the spectral where frequencies are between 300 GHz (3×10^{11} Hz) and 3 THz (3×10^{12} Hz) [1], the wavelength of which is between 3 mm to 30 um. One terahertz is equal to one trillion oscillations per second.

With the fast growing of network all over the world, larger capacity of networking bandwidth has been in great need to meet the increasing demand of modern technologies. As a consequence of it, the current wireless networking system is reaching its peak to meet the still growing need on network speed. The current speed of Internet is among several gigabits per second, however it is not sufficient. The transmitting need is still growing. Inspired by the developing of wireless network, research and developing on terabits per second links would be a good solution to the current wireless network bottle neck.

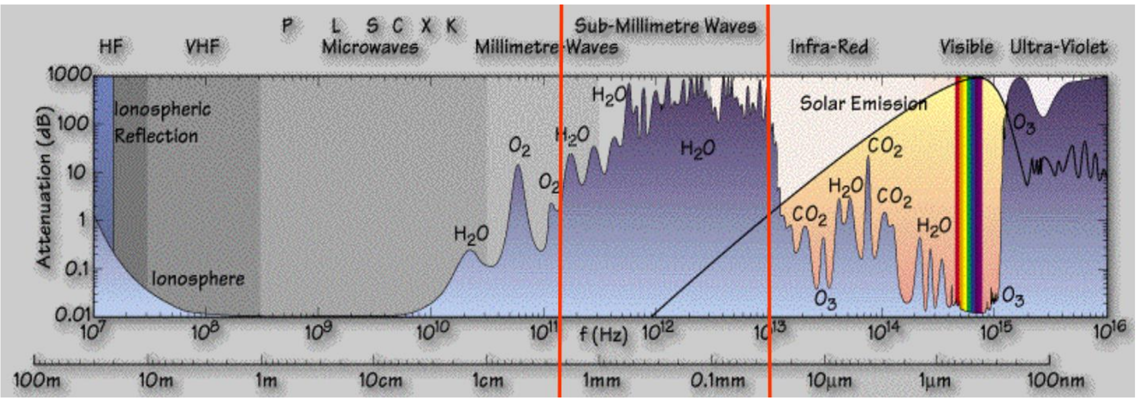

Figure 1. *Terahertz waves in bandwidth [10]*

In the electromagnetic spectrum, from low frequency to high frequency, there distribute spectrum like radio, microwave, infrared, visible, X-rays [10]. Terahertz band is bandwidth consists of frequencies in between microwave and infrared frequencies. Traditionally, the band lower than THz such as infrared band and band higher than THz such as microwave band have already been put into research to a large extent compared with terahertz frequencies. During the past few decades, terahertz has been developed in telecommunication and Nano-networks. However, it has not been developed enough compared with microwave and infrared frequencies. What's more, this band is still not licensed. There is still large room left for developing terahertz band.

The theory and technologies developed for lower frequencies (e.g. microwave length) are not applicable for terahertz band due to the small wavelength of THz band. Similarly, for the developed infrared wavelength technologies such as optical technologies are not feasible for terahertz band because the wavelength of THz is too large for it. As a matter of fact, there exists a gap of technologies for the frequencies between lower frequencies of the electromagnetic spectrum and the higher frequencies of the electromagnetic spectrum due to the lack of no appropriate signal sources to generate THz waves and a lack of detectors for it [1]. The gap between microwave technologies and optical technologies is called terahertz gap (THz gap) [10].

Moreover, despite the abundant examples of terahertz light, it is hard to make use of natural terahertz light because they are randomly distributed. The society has made large amount of profit from the lower frequencies such as microwave length of electromagnetic spectrum and the higher frequencies of electromagnetic spectrum. Because of the random distributed energy of terahertz band, not much commercial profit was obtained like the other two bandwidths.

1.2 Possible applications in terahertz networks

In the early 80th of the 20th century, due to a lack of methods to produce THz waves and the inefficiency methods of detecting them, the research of terahertz wave was very limited. Later on, the development of ultrafast laser technology has provided the possibility to research terahertz waves. It makes steady and reliable sources to produce terahertz wave possible. Research on THz band has increased visibly. Although there is no such large amount of commercial use of terahertz products as in microwave section and infrared section, but the usage of some terahertz technologies has been proved irreplaceable and future use of terahertz waves promising.

In macroscale, as a fact that terahertz is very sensitive to material, terahertz technologies can be widely used in airports, harbors, and large transits for security checks. Moreover, the research on terahertz explosives detection and monitoring on chemical biological weapons is also being carried out [1]. The terahertz band channel is highly frequency selective. Due to the water vapor molecules absorption, it is very dependent on distance. When it comes to atmospheric attenuation at THz band frequencies, large antenna arrays are used to overcome the distance dependent characteristic. In military, this increases the effort of attacks, thus military security is improved.

Wireless communications and networking, the bandwidth of terahertz can vary from several tens of gigabits to several terabits. It provides a large spectrum density in wireless communication systems. For tens of gigabits, the transmission speed is much faster than current technology. In the further future, large capacity multimedia wireless communications might be real using this technology. The terahertz transmission technology is distance dependent, the transmitted signal decreases significantly as the distance increases. But for short distance transmission, terahertz has its own advantages. For instance, Google glasses can use terahertz transmission to realize uncompressed video transmission.

In nanoscale, the terahertz technologies can be used in nanoscale machines or Nano-machines. Nano-machines are aimed at developing small machines which are able to execute one or few simple actions in a complex system [7]. Terahertz technologies are used in health monitoring. The energy terahertz photon is much lower than the energy of X-rays and Y-rays, it does not produce photoionization effect, as a result the cells will not be changed to cancer due to receiving large dose of radiation. Terahertz systems might be used in surgery to check the resection status of cancer tissues, avoiding resection of health tissues.

1.3 Important concepts in estimating terahertz bandwidth

To analyze terahertz capacities, the capacity of the given bandwidth should be estimated. Define a certain nodes and connections, the maximum rate of signal of interest received over these connections. To calculate capacities, we introduce the concept of signal noise ratio, known as SNR.

In the classic Shannon Capacity, channel capacity is calculated in this way [14]:

$$C = B\log_2(1 + S/N) \qquad \text{(bit/s)} \tag{1.1}$$

In this formula we can see the importance of SNR in calculating channel capacity. Channel capacity is defined with a given SNR value in a certain network. Shannon capacity indicates that the speed to deliver messages in networks systems not only is related with bandwidth B, but also related with S/N, Signal Noise Ratio. It proves that SNR is a crucial factor that affects the quality of communication. Compared with Signal Noise Ratio, Signal to Interference plus Noise Ratio, it includes interference while in this thesis interferences from other nodes are regarded as the overall interference. Here is the difference between interference and noise: noise often includes thermal noise in the environment, the frequency spectrum is usually wide. While interference includes the received signals from other nodes, the spectrum of which is narrow compared with which of noise.

In wireless network with n transmitter or nodes, the transmitted powers of each node are assumed as S1, S2, S3...Sn. Transmitter is designed to transmit its power to receiver, but it is transmitted as an interference to the receiver node. Other than interference from the nodes, there also exist background noise to the receiver. To measure the percentage of signal of interest received at the receiver, we use the classic Signal to Interference plus Noise Ratio (SINR). The form is given as:

$$SINR = S/(I + N) \quad (1.2)$$

In this formula, S represents the power of signal of interest, symbol “I” is the total amount of interference from every node except for the node of interest. “N” represents the noise power to the receiver.

1.4 Research of interest in this thesis

Because of the valuable applications of terahertz technology, it is beneficial to analyze the properties of terahertz bandwidth. Channel capacity is the direct limitation on the usage of certain bandwidth. As a need for more channel capacity in modern networks, it is of great importance to estimate this feature in terahertz networks. We will use Matlab simulation of estimating channel capacity and its related parameter SINR.

In this thesis, we estimated the Signal to Interference plus Noise Ratio within different distances in terahertz band. By changing the distribution of the transmitting nodes, we estimated the SINR values of a given distance. On the basis of the previous values, by applying Shannon Capacity formula, channel capacities corresponded to the related SINR were calculated. Finally, we plotted the Cumulative Distribution Functions of the capacities and SINR values.

Structure of this thesis:

The main sections of the paper are summarized as the following: to begin with, in Chapter 2, a deeper look into the state of art on terahertz band research will be illustrated in more detail. Moreover, we will clarify the unique propagation model in terahertz network. The pros and cons of this propagation model will be revealed. By the end of this chapter, more about Signal to Interference plus Noise Ratio and the concept of capacity in terahertz band will be mentioned.

Secondly, we use Matlab simulation to create the scenario needed in this paper. N nodes following Poisson Point Process were created, the node in the center is designed as the receiver, and the SINR from nodes at different distances were estimated in this scenario. In this chapter, a detailed structure of the scenario will be explained.

Thirdly, we will present our results from the previous scenario setup. The performance of terahertz band is analyzed based on the obtained results of SINR, CDF of SINR, capacities and CDF of channel capacities. There will be a discussion over the SINR values in Matlab simulation as the values do not exist this scenario setup. Last but not least, we draw the conclusion at Chapter 5. Achievements from this paper will be summarized meanwhile the imperfections of the system will also be proposed.

2. COMMUNICATION IN THZ BAND

With the development of modern technology and growing need in faster transmission speed in wireless network system, communication in terahertz band has drawn more and more attention of researchers and investors widely.

2.1 Terahertz and its history

About one hundred years ago, terahertz wave was mentioned when research on infrared lights was conducted. However due to lack of detectors and transmitters, terahertz technologies were not investigated enough. Consequently, the applications of terahertz wave were even less. This situation has not been changed until recent 20 years. The number of organizations conducting research on terahertz wave increased from 3 to more than 200.

Multiple unique features exist in terahertz band. It ranks one of the “Ten technologies which will change the future” in the US. Terahertz spectroscopy, terahertz imaging and terahertz communication are three main research aspects in modern society. Because of the high frequency of terahertz, it also has high spatial resolution. Meanwhile because of the short pulses of terahertz wave, the time resolution of which is high. Terahertz imaging and terahertz spectroscopy are two key technologies in terahertz application. Meanwhile, because the energy of terahertz wave is small, it will not do great damage to materials when conducting examinations. Compared with traditional X-ray examination, it is much safer.

Terahertz technology provides great challenge and opportunities for developing at the same time. The applications of which include innovation on technology, domestic development and national security. Terahertz technologies might cause a revolutionary change in science and technology world. The length of terahertz wave is between micro wave and infrared light. Due to its special wavelength it is complementary to microwave and infrared light. Compared to traditional micro wave and infrared light, it achieves higher resolution. Besides, the anti-reference ability and special anti-stealth ability make it stand out in new technologies. In comparison with laser, terahertz has a wider view. What’s more it is better at searching and can be used to extremely bad weather conditions. In nanoscale communication, terahertz technology is already put into use. Some of the application of terahertz technology are already putting into use, and it will prosper as research goes on.

2.2 Terahertz detectors and sources

Two crucial parts for researching terahertz applications are terahertz detectors and sources.

Terahertz waves and the detection of which can be divided into two categories in general: continuous THz wave generation and pulse wave generation. For the methods of generating and detecting terahertz signals, there are two ways: optical method and electronic method [1].

In optical method, the methods such as Austin switch, Photomixing, Optically pumped THz lasers (OPTL). For the electronic method, it consists of Gunn diodes, Schottky diode frequency multipliers and Quantum Cascade Lasers (QCL) [1].

2.2.1 Terahertz detectors

Due to the special wavelength of terahertz waves, the detection of waves at equivalent bandwidth is evidently different from that of shorter wavelengths such as optical waves and longer wavelength such as radio waves. Compared with longer wavelengths, terahertz detectors do not have handful electronic components including resistors, capacitors and inductors. Meanwhile compared with shorter wavelength, because of the lower frequency of terahertz band, there is a lack of photon energies which leads to thermal noise which is becoming the principal factor in detecting.

There are the following main detectors in terahertz techniques:

Thermal detectors [1]:

- The Golay Detector
- Pyroelectric Detectors
- Thermopiles
- Power Meters
- Semiconducting Bolometers
- Superconducting Bolometers
- Room Temperature Microbolometers

Photoconductive Detectors [1]:

- Extrinsic Germanium Detectors
- Indium Antimonide Detectors
- Gallium Arsenide Detectors
- Blocked Impurity Band Detectors

Heterodyne Detection [1]:

- Heterodyne Detection Theory
- Schottky Diode Mixer
- Superconductor-Insulator-Superconductor Mixer
- Hot Electron Bolometer Mixer

Optical and electronics detectors are used in pulse THz technology. The effects of environmental thermal noise can be excluded and a higher SNR result can be obtained. Coherent measurements can be made. The various amount of thermal detectors can detect terahertz radiation emitted by various light sources and measure various spectral ranges of radiation. However, compared with differential measurements, they have a lower detection sensitivity.

2.2.2 Terahertz sources

The sources for terahertz waves remained to be thermal sources until around 1950. It included either heated solids which retain food emissivity or hot plasma of discharge lamps. After the invention of laser in 1960th, gas lasers made it possible to generate sources to cover the whole terahertz region. In the 1990th, solid state sources which includes p-Ge lasers tunable and quantum cascade lasers(QCLs) became available which makes the progress even greater.

Terahertz sources includes the following main categories:

- Practical thermal sources, which includes the Globe and Plasma sources
- Gas lasers which includes Electrically Excited Gas lasers, Optically Excited Gas lasers
- Bulk Semiconductor Lasers which includes Germanium Lasers and Lasing from Optically Excited Donors in Silicon
- Quantum Cascade Laser
- Photomixing for the generation of terahertz radiation

There are the following four main methods to produce continuous terahertz waves:

- Fourier transform infrared spectrometer, using a thermal radiation source, such as mercury and silicon carbide rods
- Nonlinear optical mixing
- Electroporation sub oscillator radiation, such as anti- wave tube, Gunn oscillator and Schottky Diode
- Gas laser or a semiconductor laser

There are the following ways to generate terahertz pulse waves:

- Photoconductive Antenna Method
- Optical Rectification Method
- THz parametric oscillator method
- Air plasma method

Among these methods, air plasma produces relatively high intense THz waves, this method has attracted attention from institutions and researchers.

	Optically pumped terahertz lasers	Time domain spectroscopy	Backward wave oscillators	Direct multiplied sources	Frequency mixing
Average power	>100 mW	~1 µW	10 mW	mW–µW (decreasing w/increasing frequency)	Tens of nanowatts
Usable range	0.3–10 THz	–0.1–2 THz	0.1–1.5 THz	0.1–1 THz	0.3–10 THz
Tunability	Discrete lines	N/A	200 GHz	~10–15% of center frequency	Continues
Continues wave/pulsed	CW or pulsed	Pulsed	CW	CW	CW
Turnkey systems available	Yes	Yes	No	Yes	Yes

Figure 2. *Terahertz generators in bandwidth [10]*

2.2.3 Advantages and limitations of terahertz technologies

The current terahertz generation methods can be roughly divided into the above categories, each of them has its advantages and limitations:

Free-electron laser and gas Laser can generate relatively strong THz waves and covers a wide range of frequencies. However, it requires larger volumes and has high power consumption. Due to its potential use of terahertz and Infrared Quantum Photodetectors in far-infrared imaging in room temperature, it has attracted lots of attention.

Quantum Cascade Laser, which is able to generate milliwatt-level powers. It is higher than the microwatt-level powers produced by other methods. Besides, it has the advantage to generate cheap, room temperature sources. The main goal for this technology is to broaden the bandwidth of terahertz band.

The potential usage of terahertz technology and its bright future have drawn the attention of scholars and technology companies. It has been investigated to a large scale especially in north America, Europe and Japan. In the coming text we can take a look at different applications of terahertz technology.

2.3 Applications of terahertz technology

Terahertz technology has usage of great importance on physics, chemistry, biomedicine sciences, environmental science and material science. Terahertz waves can be special and effective detectors for detecting internal substances. It provides information about the chemistry substance and bio-substance of materials. Terahertz technology can also analyze spectral characteristics, molecular dynamic process etc. THz radiation under strong magnetic field made extraordinary contributions to high power.

Terahertz technologies can be applied in least in the following aspects:

In biomedicine:

It is well known that biological systems are made of variety of complexes of macromolecules, cells and tissues. Two types of motions exist in a biological molecule: one is vibration modes happen to be on femtoseconds to tens femtoseconds. The other is structural dynamics of a protein appears ion time scales from nanoseconds to milliseconds. For the low frequency mode occurs on picoseconds time scale falls within terahertz region spectrum [9].

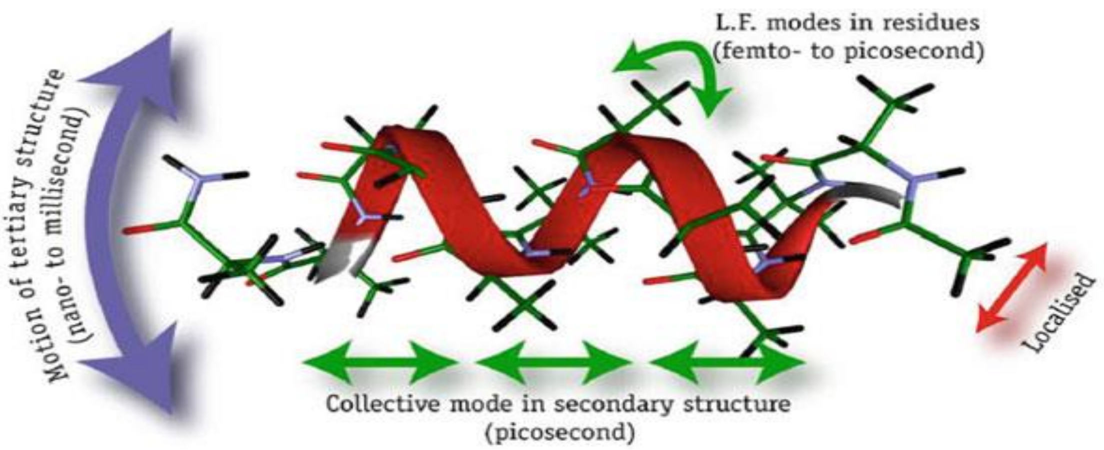

Figure 3. *A biological molecule with related dynamical time scales [9]*

In medical and security area:

Terahertz technology is applied to cancer diagnosis and genetic analysis. Because of the same resonance frequency of molecules and terahertz waves, it can be used to extract important substances from DNA. According to some research, if coffee is mixed with some medicine, the mixed liquid could turn to poison. Applying terahertz technology to detect medicine and early diagnosis on cancer might have breaking news.

Terahertz technology can be also applied widely in medical use. Plenty of attention is drawn to cancer in modern medical world. For instance, breast cancer has caused the second most death just following lung cancer. To achieve better treatment, detection of breast cancer as early as possible is vital in the treatment. Traditional detecting technologies such as X-ray was used in the past years. X-ray detection has a high resolution because of its relatively short wavelength. However, a radiation hazard might also be caused by X-ray. In recent years, terahertz detecting is used while not ionizing the images to compensate the disadvantages of it. Compared with hazard X-ray detection, THz technology is less risky. Terahertz cannot replace X-ray, but it has its own advantages over X-ray.

While Ultrasonic wave and X-ray can be used to detect the shape and statues of materials, it cannot specify material kinds. For instance, it cannot be used to detect the difference between explosive material and normal medicine. Terahertz can achieve this goal. If made use of this feature, it is of great importance in the fight against terrorism. Terahertz is able to detect almost 50 kinds of explosive materials. It can be applied in military and national security. The United Kingdom is the first country to develop THz cameras. They are used in security checking in airports.

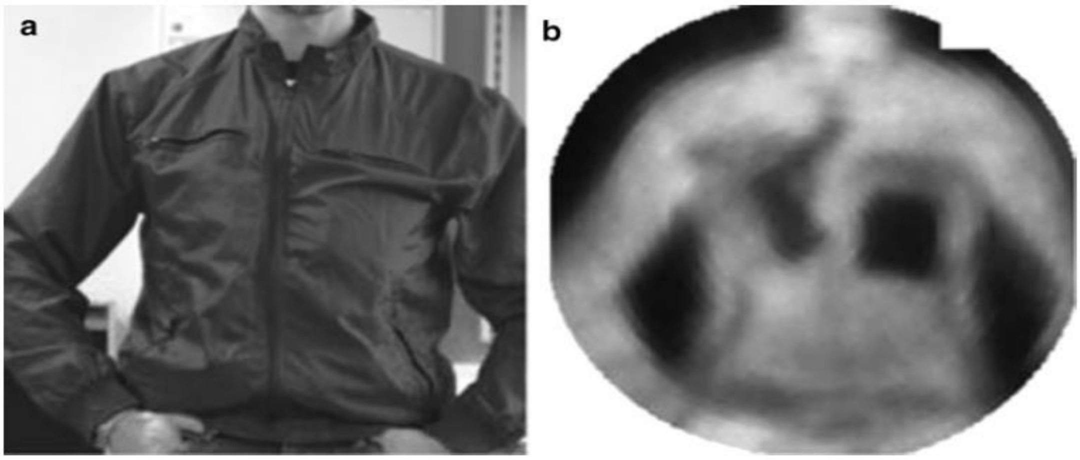

Figure 4. *(a) Image of the person with hidden objects under the jacket.*
(b) THz image of the same person [11]

Additionally, Oak Ridge National Laboratory (ORNL) and the University of Tennessee cooperate on the program “Through wall Program” which is aimed to obtain the information inside of the wall. This technology is of great value in national security.

In nanoscale technology:

Communications between nanomachines will be possible in THz band: small function devices are able to execute simple tasks. It is not we do not put nanomachines in in THz band for communication. It is because of the size and features of nanomachines, it is necessary for them to be researched in THz band.

Resonance frequency is an important factor in terahertz band. Because the resonance frequency of biological molecules and rotational frequencies fall in terahertz band, terahertz waves can be used in selecting food and beneficial bacteria and in agricultural and food industry in the near future.

The connection between nano devices and current existing communication networks in the Internet determines a new networking mode is referred to as the Internet of Nano-Things, known as IoNT. In the terahertz band (0.3-3 THz), the medium graphene can be used to make high-tech Nano-transceivers and Nano-antennas. Both of them work very well in THz channel [4]. With Nano-transceivers and Nano-antennas, objects can be connected to the Internet by inserting Nano-transceivers and Nano-antennas into objects [7].

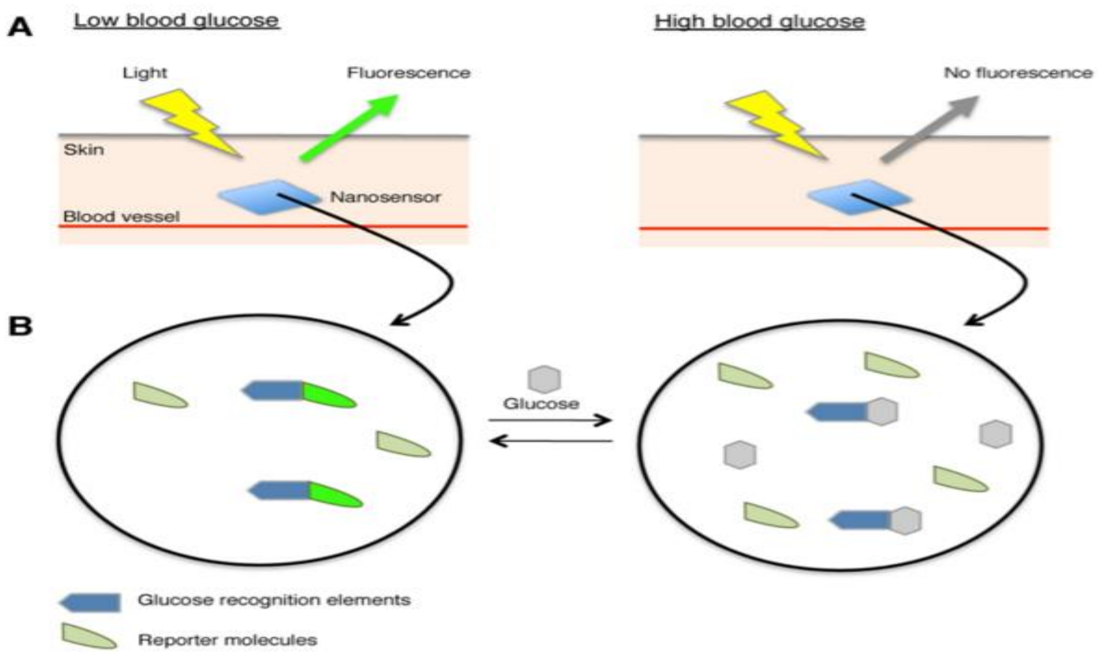

Figure 5. *Usage of THz in biomedical detecting [4]*

In Environment:

THz radiation can penetrate smoke, therefore it can be used to detect harmful and poisonous molecules. Existing substances in the atmospheric level such as water, carbon dioxide, methane, sulfur dioxide and oxygen can be detected by the molecular resonance in terahertz band. Regarding to protecting environment and monitoring environment, terahertz technology plays an important role. Nowadays terahertz sensors used for data collection are put into use for the production process.

Using THz technology for environmental protection has the following advantages:

- Accuracy -- the picometrix THz sensor
- Precision -- by applying triplicate THz sensor measuring the related material
- Comparability -- terahertz methods can be combined with other technologies for environmental related testing

With the worsen situation of environment, there will be great demand in the future in analyzing and monitor the environment status.

Application of terahertz waves on art:

Mid-infrared spectroscopy is mainly used for identifying organic and inorganic materials. It is known as more traditional spectroscopy. Compared with mid-infrared spectroscopy, terahertz spectroscopy can be used for analyzing composites such as pigment binders and mixtures. Not only can terahertz technology be used as cutting edge technology, it can also be used for art conversation [6].

Besides the current trend that terahertz spectroscopy is used for security check such as detecting weapons and illegal drugs, THz imaging is also utilized for art conversation and restoration. Inorganic pigments such as colors have fingerprint spectra in the THz region [18].

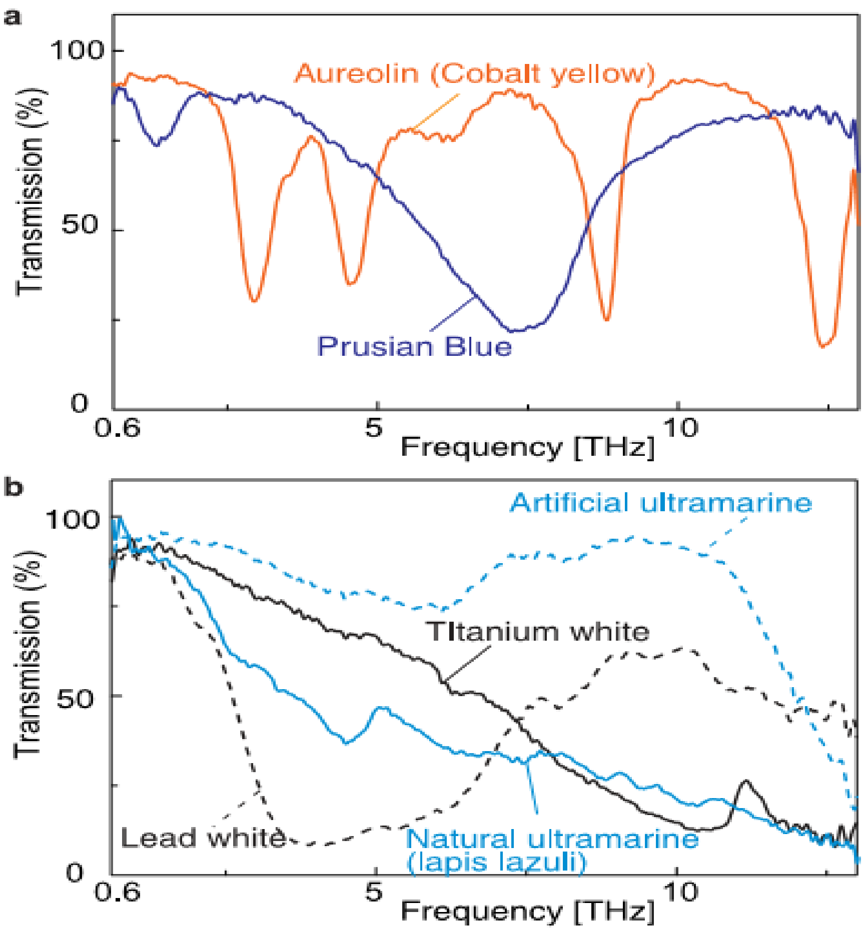

Figure 6. *The finger print spectra of aureolin and prussian blue [18]*

2.4 SINR and capacity in terahertz band

To estimate the quality of the channel, we will take a deeper look at two important parameters of terahertz band: Signal to Interference plus Noise Ratio (SINR) and channel capacity.

2.4.1 Signal to Interference plus Noise Ratio

SINR is first used in multiple user detection. For instance, assuming that there are two users, user A and user B which are used as receivers. The data user A received from the transmitter to user A is interest of signal while the signal from transmitter to user B is interference. Besides from interference from equivalent nodess, there exists the background noise additionally.

SINR is a crucial parameter. For receivers which has high demand for sensitivity and anti-interference of devices. CDMA is a system of limited interference system. Multi-user interference has a large impact on the system. Meanwhile as the base stations use the same frequency, different stations affect each other on a large scale.

To have better knowledge of SINR, it is necessary to have the basic understanding of SNR (Signal Noise Ratio), a parameter close to SINR. SNR is the result of noise divided by signal of interest.

SNR is used in the famous Shannon formula to calculate bandwidth capacity [14]:

$$C = B\log_2(1 + S/N) \qquad \text{(bit/s)} \tag{1.1}$$

Although we did not use SNR to calculate the channel capacity. Shannon capacity includes the concept and application of SNR. Shannon formula indicates that the capacity of a band not only is related to bandwidth itself but also related to SNR. It also proves that SNR is a crucial element to influence communication quality.

SINR which has only one parameter I(interferences) more than SNR, Signal to Interference plus Noise Ratio. Noise is mainly determined by thermal noise. The frequency spectrum is usually wide. Compared to noise, interference is often determined by signals from other systems, the frequency spectrum is narrow compared to that of noise.

There is no defined definition for SINR at this moment, the most commonly used determination is as following:

$$\text{SINR} = \text{Signal} \,/\, (\text{Interference} + \text{Noise})$$

In this paper we calculate SINR using the following way:

SINR = Receivedpower/(Power_interference+PowerN1+Noise_overall);

SINR_DB = 10*log10(SINR);

The received power is the power received from signal of interest to the receiver. Power of interference is the overall power from other nodes within given distance. PowerN1 is the overall noise including background noise and self-induced noise.

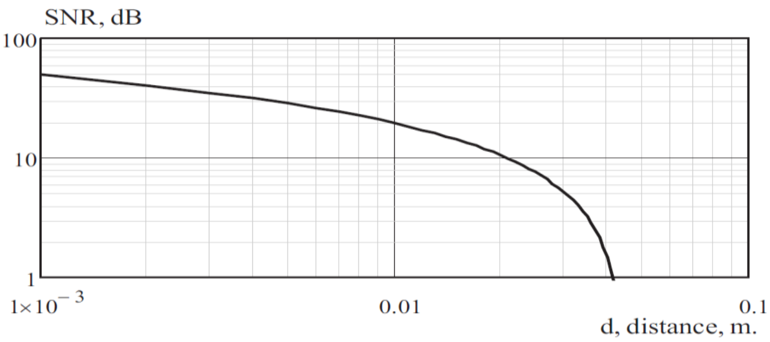

Figure 7. *SNR versus distances [7]*

2.4.2 Shannon capacity in terahertz band

After a basic understanding of SNR and SINR, we can introduce the concept of channel capacity which is used to estimate a crucial feature in networks.

Channel Capacity:

If A is communicating with B, the actions of A have caused a wanted action in B. This action of transferring information as a result has caused ambient noise. Due to the limitation of systems in reality, there will be noise related to thermal noise [16].

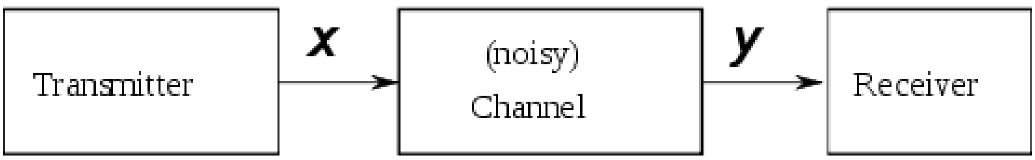

Figure 8. *Simplified communication model from transmitter to receiver*

Channel capacity is the maximum information rate can be transmitted over a communication channel where to achieve arbitrarily small error rate (BER) [14]. Before Shannon theorem, it was generally believed that with the increasing of information rate, the error rate also increases. In other words, to decrease the bits per second error rate, it is needed to decrease the information transmitting rate. However, Shannon's theory proves that is not correct. If the maximum rate of the channel is reached, which is known as channel capacity, it is impossible to avoid error probability. If information rate is not bigger than channel capacity, by inducing intelligent skills, one is able to reach arbitrary small error probability. Shannon capacity is defined as the maximum error free data rate that a channel can support.

We use Gaussian Channels in this model. Gaussian channel is a time discrete but state continuous channel. $Y = X + N$, X is the input signal, Y is the output signal with Gaussian noise represented as N. The mean value of this Gaussian noise is zero. Probability distribution function of N is illustrated by the mean value and variance. Gaussian channel has limited power.

Shannon-Hartley theorem:

$$C = B \log_2(1 + S/N) \qquad \text{(bit/s)} \qquad (1.1)$$

In the formula, C represents the channel capacity, in which B is the channel bandwidth in THz, S is the power of transmitted signal and N is the power of noise. The unit of C is per second (bits/s).

According to the formula, two factors are crucial to increase the capacity: bandwidth and SNR, increase either bandwidth or SNR can lead to the increment of capacity. At the same time, decrease noise power can also increase capacity. If the power spectrum density of noise is close to zero, then capacity is close to infinite, it proves that the capacity of a channel without noise is infinite. If increase the bandwidth of the channel, capacity will increase, but not proportionally. It can be proved that if B is infinite, the value of capacity is not infinite.

Instead, $C -- > 1.44 \frac{S}{n_0}$

This Shannon capacity theory is one of the most important concepts in wireless communication networks. When the bandwidth of the channel, power of the signal of interest is given, information can be transmitted at the rate C or lower than C with the smallest error zero when the coding system is intelligent enough. But, if the transmit rate is higher than C it is impossible to transmit information without error. The meaning of Shannon's theory gives the limit rate of a defined bandwidth and defined signal power. It is also the foundation of spread spectrum techniques.

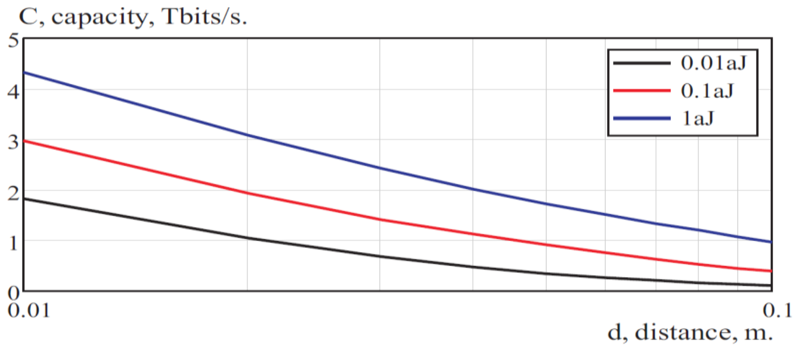

Figure 9. *Channel Capacity with different energy from signal of interest*

3. CHANNEL CAPACITY AND SINR IN TRAHERTZ BAND

A stochastic model will be developed for estimating the loss mentioned in Chapter 2 [6]. In the following chapter we will discuss this model which applies for our topic.

3.1 The environment of terahertz channel in this thesis

We build the environment follows below description:

A Poisson Point Process is generated on the space with some intensity lambda points/meter*meter. Points represent nodes of receivers and transmitters [15].

The distribution of transmitters will be defined by this parameter. The node in the center of the given space (which is a square in this paper) is chosen as the receiver. This receiver will receive signal from the signal of interest as the valid received signal or the received signal of interest. In the meantime, interferences from other nodes will affect the receiver. When sending signals, the nodes of transmitters follow Poisson Process. We created a circle with the receiver as the center of the circle, R as it’s radius. This circle contains a Poisson distributed number of nodes.

By choosing different radius the severity of other nodes which affects the receiver will change. The radius R is determined so that transmission of nodes outside of R does not influence the reception at the node of interest significantly. Inside the circle, there is a transmitter of signal of interest at the distance of r. The SINR in such a system is represented in a classic way with the exception of noise in the denominator depends on the sum of the power at the receiver.

In this particular scenario we defined the area of the square is 50 multiply 50. Lambda represents the density of the nodes in this area. It is a changing parameter to monitor the SINR and channel capacity differences with different densities. The distance of the signal of interest to the receiver is also changing.

The script of Distribution of nodes of interest:

```
Points_N = poissrnd(Mean_points,[1,2]);
%The coordinates of the node are stored in a 1*2 matrix
Points_N(1) = unifrnd(0,X_length);
%Get the uniform distribution value of X coordinate
Points_N(2) = unifrnd(0,X_length);
%Get the uniform distribution value of Y coordinate
```

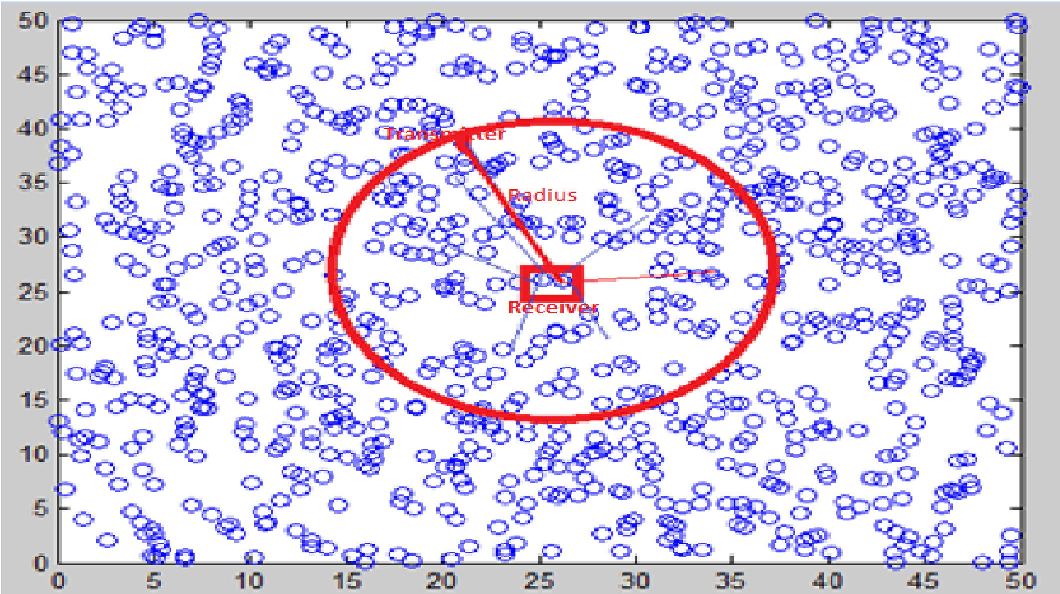

Figure 10. *Environment of simulation*

The parameters included in this scenario are:

- Square of the area: 50*50 square
- Lambda: Points intensity points/meter^2
- X: Length of the square
- Mean points: Mean value of the Poisson Point Process
- N = X_length^2*lambda: Number of points generated in the environment

3.2 Propagation model in terahertz band

Now that we know the important concepts of terahertz band and the scenario in this thesis, it is time to take a detailed look at how signals are transmitted in terahertz band. Because of the high frequency of terahertz band compared with traditional wireless communication, the simulation model used for lower frequencies do not apply. The propagation in terahertz band is determined by the characteristics of the channel itself such as materials.

Although we research on the relative distances between signal of interest and receiver, as the limitations of the channel we consider the distance no more than one meter in our thesis, the reason will be explained.

3.2.1 Important concepts in terahertz propagation

The propagation loss in terahertz band includes three parts: propagation loss, absorption loss and noise affection. We developed the channel model for terahertz band as the following:

Propagation model:

Chosen a transmitter as signal of interest, a receiver, the propagation model can be defined. The received power can be calculated like this [5]:

$$PRx\,(f, d) = PTx(f) - LP(f, d) - LA(f, d) \tag{3.1}$$

In this equation, d is the distance from the transmitter to the receiver, f is the frequency of the network. PRx (f, d) represents the received power, LP(f, d) is the spread loss at distance d and LA(f , d) is the absorption loss in the channel [5]. In the coming context the main three sections in the receiver signal of THz network will be illustrated.

Spread loss:

One significant propagation loss in communication systems is the propagation loss [8]. The signal strength decreases with distance. This loss is caused by fading and channel dispersion. Depending on the propagation systems the fading features differ. The cause of spread loss is because the signal attenuates when it is propagating through a certain medium.

There are the several crucial factors in describing a propagation model [12]:

- Propagation is time delayed, the structure and probability distribution of time delay spread
- The geometrical path loss of the system [8]
- Shadow fading and operating frequency [12]

The model of spread loss in terahertz band is similar with that of lower frequencies. The spread loss results from the line-of-sight path through mediums without obstacles, in this thesis we consider air as the transmission medium. The spread loss in the channel is determined by two key parameters: distance and frequency. The frequency response for spread loss can be defined as following [5]:

$$H(s) = \left(\frac{1}{\sqrt{4\pi d}}\right)\exp(2\pi df / c) \tag{3.2}$$

In which H(s) is the frequency response of spread loss, c is the speed of light, 299792458 m/s, f is the frequency in the related transmission system which represents frequencies from 0.3 to 3 terahertz, and d is the distance from transmitter to receiver. We choose the relative distances of 2 to 24 in this thesis.

As illustrated from the formula, with the increasing of distance, the propagation loss increases remarkably, one reason why limit the distance from transmitter to receiver within one meter. Because of the restriction of distance on spread loss, the high propagation loss limited the distance signals can be transmitted in terahertz band.

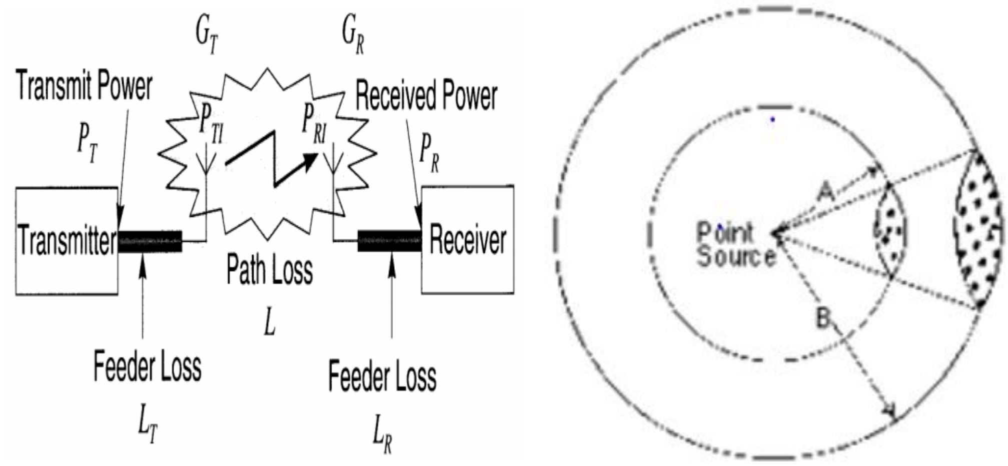

Figure 11. *Spread loss in space [8]*

For explanation of the scripts see the appendix [1].

The script to calculate spread loss:

```
[maxx,f0] = max(X(1:NFFT/2+1));
%maxx is the highest value of X, and f0 is the
%index of maxx
spreadLossDB=20*log10(4*pi*Dis')*ones(1,length(f))
+ones(1,length(Dis))'*20*log10(f(f0)*ones(size(f))./c);
%Calculating DB of spreadloss
```

Absorption loss:

Absorption loss is the loss when energy of photons is transmitted or absorbed by the substances during electromagnetic radiation [5]. Absorption loss is unique in terahertz band compared with traditional lower frequencies as the molecular vibration frequency falls in terahertz bandwidth. It is influenced by the concentration and special mixture of molecules along with transmission. The absorption loss in this bandwidth is tremendous and cannot be ignored. In this model we consider the substance of absorption is molecules [1]. When considering energy transforming, the electromagnetic energy is transmitted into the kinetic energy of molecules. This model focused on the 400 GHz transmission window [5].

The absorption loss is the most dominating parameter in terahertz band. Compared with channels with lower frequencies, the most significant difference in terahertz channel is the molecular absorption loss: as the internal vibrating frequency of molecules is close to the frequencies of terahertz frequencies. The vibrating molecules absorb the energy of transmitted signals and transfer it to kinetic energy of the molecules [5]. In this section we will estimate the molecular absorption loss in terahertz channels. The absorption loss is much related to the molecules themselves. Absorption coefficient, an important parameter in estimating molecular loss. It is calculated as the following: sum up the individual absorption coefficient of each molecule.

Given as the following equation [5]:

$$k\,(f)=\sum \frac{p}{p_0}.\frac{T_0}{T}.M^i\delta^i(f) \tag{3.3}$$

In this formula, representing the coefficient of kinetic movement, f is the frequency, p is the current atmospheric pressure, p0 is the reference pressure at one atmosphere, To is the pressure at 273.15 K, stands for the number of molecules per volume unit of gas i, represents the absorption cross-section of gas i.

After knowing the medium absorption coefficient, the absorption loss of the system can be calculated like this [5]:

$$H_{abs}\,(f,d) = \exp(-\tfrac{1}{2}k(f)d) \tag{3.4}$$

k is the molecule absorption coefficient of the system, H_abs is the absorption loss of the system, f is the frequency of communication window, and d represents distance.

The molecular absorption loss will be defined by the below parameters: frequency, distance and medium absorption coefficient. A major part of absorption loss comes from water vapor molecules. For explanation of the scripts see the appendix [1].

Script to calculate molecular absorption loss:

```
tau = sum(kvt(1:8,:),1);
% Absorption coefficient [cm^-1]
absLossDBM = 10*tau*1e2*log10(exp(1));
% Absorption Loss [dB m^-1]
absLossDB = (Dis)'*absLossDBM;
% Absorption Loss (dB)
```

Noise in terahertz network:

As various platforms are applicable for terahertz networks in astronomy and upper atmospheric research, room temperature system developing become more important. We build the noise channel in room temperature, which means T0 is approximately 296 (Kelvins).

When the channel is not being used, there exists only the background noise while if the channel is being used there exists both background noise and molecule noise. The main environmental noise in terahertz band is from molecular absorption noise. Part energy of the signal of interest is transformed to molecular absorption noise.

This kind of noise is related to the molecules and the physical material of them. When a signal is transmitted, both molecular absorption loss and background noise exist. However, if the channel is idle, there will be only background noise. Besides from the above mentioned background noise, there is also the self-induced noise by the channel itself. The background noise is not only crucial in calculating network bandwidth but also limits the eventual detection of photoconductive detectors [5].

From the previous discussion we have the absorption coefficient. In the noise model, the molecule absorption coefficient is a crucial parameter as well. k is absorption coefficient [cm^-1]:

```
tau_d = exp(-(Dis)'*1e2*k);
```

e = 1-tau_d, e is for the calculation of background noise, which is calculated in the following way:

```
S(background) = k*T0*e*|Hant(f)|^2;
```

The background noise is independent of transmission distance.

There is also another self-induced noise which is due to the transmission at certain distances.

```
S_N1 = e.*(c./(4*pi*(Dis)'*f(f0)*ones(size(f)))).^2.*S_X;
```

4*pi*d'*f(f0) includes antenna response at both transmission side and receiver side. The overall noise of the system is the sum of background noise S(background) and self-induced noise S_N1.

The overall noise in the system is the sum of molecule absorption loss, self-induced noise and system background noise. After knowing all three kinds of losses in signal transmission, the overall loss of the system can be calculated.

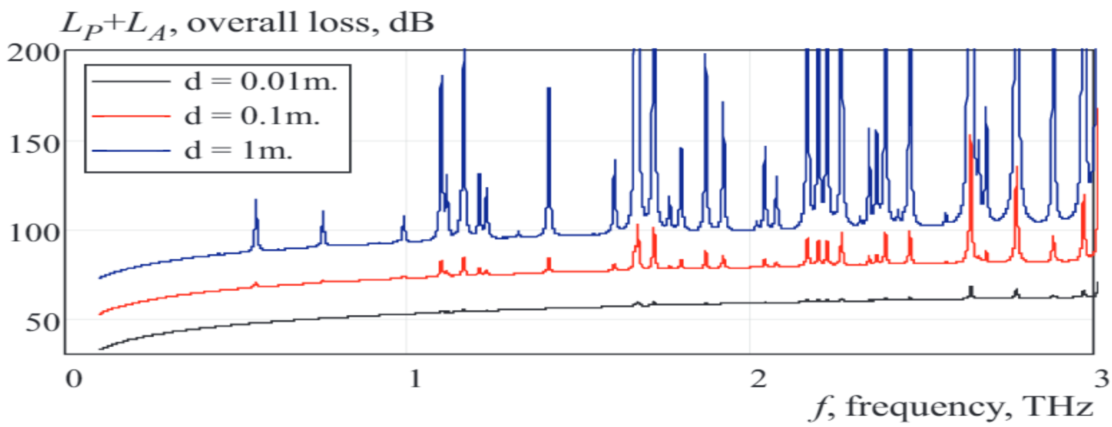

***Figure 12**. Overall loss in terahertz band*

3.2.2 Poisson point process

In the ancient times, our ancestors had tries to record natural events such as floods, earthquakes and stars in region of the sky. In scientific nowadays, scientists invented a method to imitate natural events: point process [17]. A model of unpredictable points distributed randomly in a certain space, this process is called point process. To solve counting process, one important point process – Poisson Point Process will be introduced. A Poisson Point Process with the nodes density λ, the number of points of which in a time interval (0, t) has a Poisson distribution the parameter of which is λt [3]:

$$P\big[N(0,t)\big) = k] = (\lambda \mathrm{t})^k e^{-\lambda t}/k! \qquad (3.5)\ [3]$$

Two important characteristics of Poisson point process are [22]:

- The numbers of events happening in different regions are independent. They do not interfere with each other.
- In a specific region, the numbers follow Poisson distribution. To imitate the nodes distribution, we applied the above stated Poisson point process.

Poisson process [15] is chosen for the sending packets in networks. A Poisson network model is developed for multi Poisson processes. Poisson Point Process is a useful model for a given event occurs random times. For instance, the times and locations when the police office received phone calls can be modelled using Poisson Point Process.

Poisson process is an important concept which is frequently used in probability. In Poisson process, time between two events follows exponential distribution. Each of the arrival times is independent from other arrival times [15]. Poisson process can be used to estimate the arrivals of customers. In networking, packets can be also analyzed using Poisson process. This model makes the performing of exacting sampling from arbitrary structures possible.

There are several assumptions to support Poisson Point Process [17]:

- The rate function of each process depends on a short time of the past.
- The rate function of each process only relies on the parent node.
- The rate function of each process relies on the empirical function of the parent node.
- The rate function of each node is parameterized by a generalized linear model

The Poisson Process can be illustrated according to the following graph when the variance of the process is different:

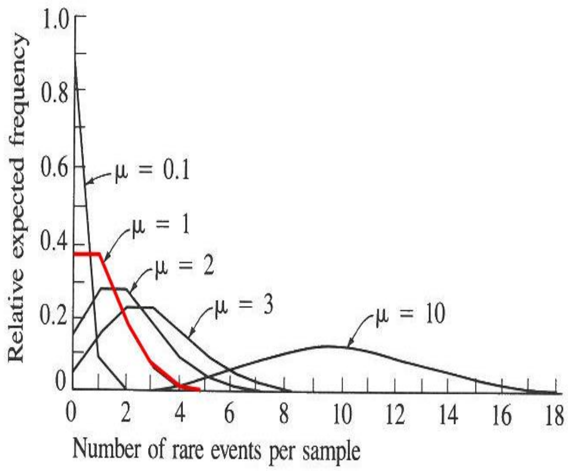

Figure 13. *Poisson process with different variance*

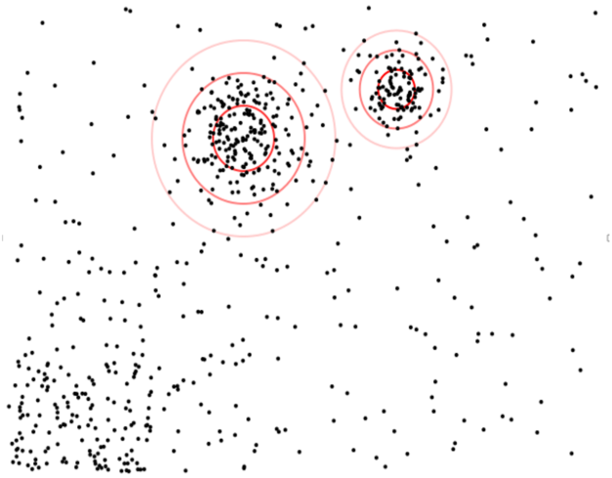

Figure 14. *Distribution of Poisson Point Process*

3.3 Signal Interference versus Noise Ratio (SINR)

From the previous content we had a brief introduction to the most important concepts related to terahertz networks. Next we are going to illustrate the simulation setups of this paper. Hopefully readers will have a clearer idea of how the simulation is performed.

In recent years, research on terahertz, the frequency of which is between 0.3THz to 3 THz has increased. One of the major reasons is that THz is useful in analyzing spectrum and ultra-wide wireless communication. In traditional network, one major difficulty for producing terahertz wave is because lack of liable solid sources instead of monitors. This area is called terahertz blank area.

Nowadays, photonic technology has been the foundation for researching THz waves. By applying ultrashort pulse lase technology, terahertz waves can be produced and detected. The pulse based method to produce electromagnetic waves is similar to the experiment first used to prove the existence of electromagnetic wave.

There are several methods to calculate the capacity of a given terahertz band. Because we calculate it based on Shannon Capacity, it is necessary to calculate the related SINR according to a certain model. In this paper, we use Matlab simulation to generate terahertz frequencies. The noise and interference of the system will also be introduced in more details later.

3.3.1 Signal Interference versus Noise Ratio (SINR) versus distances

According to the calculation of Signal Interference versus Noise Ratio:

SINR = Signal/(Interference + Noise) (3.6)

With the increasing of distance from transmitter to receiver, the effect of signal of interest decreases, and the effect of interferences increases, the SINR value is smaller in this case.

A variable is defined normally distributed with the mean value and variance when the density function follows [23]:

$$f(x) = \left(\frac{1}{\sqrt{2\pi\delta}}\right)\exp\left[-\frac{(x-\mu)^2}{2\delta^2}\right] \tag{3.7}$$

Gaussian pulse function is used for the transmitted signal. With the properties of maximum steepness of transition and the minimum group delay. For the emitted signal, we used Gaussian pulse function the sigma of which is 100 fs, the center value of which is 800 fs. These two parameters define the Gaussian pulse function.

The program Gaussian pulse calculation script is as following:

```
sigma = 100e-15; % Parameter sigma for Gaussian pulse
function
t0 = 800e-15; % t0 for Gaussian pulse function
Emax = 1e-19; % Maximum energy
lend = 100; %number of space distances
c = 2.997925e8; %[m/s] speed of light
fs = 1e14; %sample rate -- 10 times the highest frequency
ts = 1/fs; %sample period
t = (0:1:2^16)*ts; % Time sequence
tmax = max(t); %for normalization purposes
L = length(t); % the length of time vector
NFFT = 2^nextpow2(L); % returns the smallest greater than
or equal to the absolute value of 2 powered by L
```

```
Nderiv = 1;
%% Positive going monopulse
x=1/(sqrt(2*pi)*sigma)*exp(-(t-t0).^2/(2*sigma^2));
%Gaussian pulse
```

To begin with we calculate the SINR value, we use a function to calculate the received power of signal of interest. Besides we use the same way to calculate the received interference.

The channel impulse response is calculated using Inverse Fourier transform. Power spectral density (PSD) illustrates the percentages of variation as a function of frequency [2]. By calculating PSD the strong frequency variation and weak one will be shown. The received power is achieved by the calculating power spectrum density. The received power is the transmitted power minus the path loss during transmission [8].

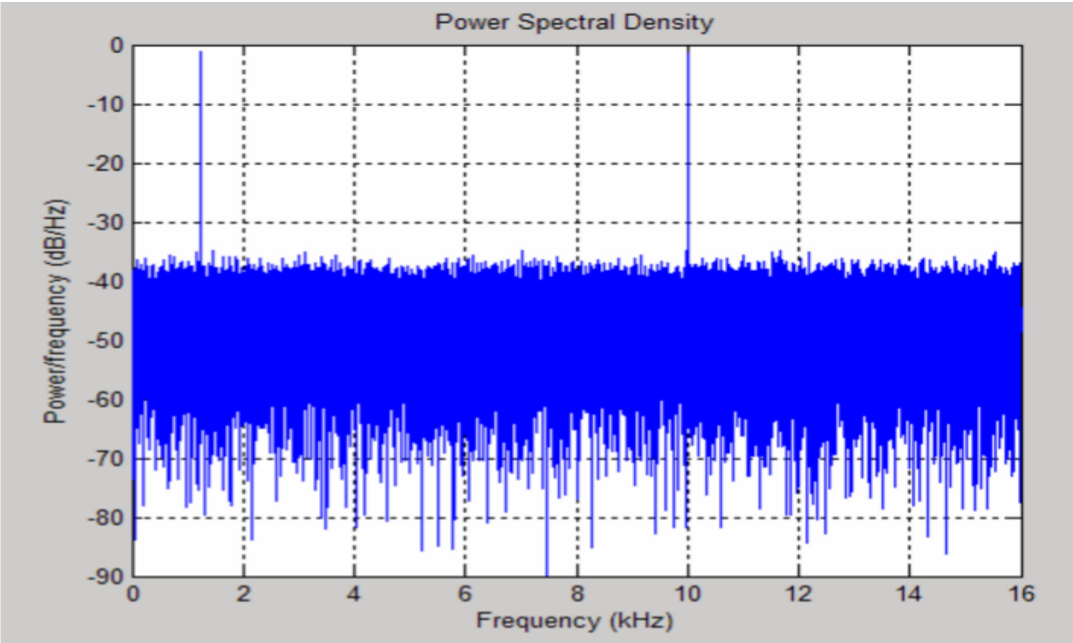

Figure 15. *Power frequency density at different frequencies*

As discussed in Chapter 2, the path loss includes the absorption loss and spread loss.

The spread loss can be obtained following the previous formula (2.2) [5]:

$$H(s) = \left(\frac{1}{\sqrt{4\pi d}}\right)\exp(2\pi df / c) \tag{2.2}$$

d is the distance from the transmitter to the receiver, f is the frequency of the band, c is the speed of light.

To describe the relationship between distance and path loss, we monitored the path loss when the distance increases. From the graph we can see that with the increasing of d the propagation loss increases dramatically.

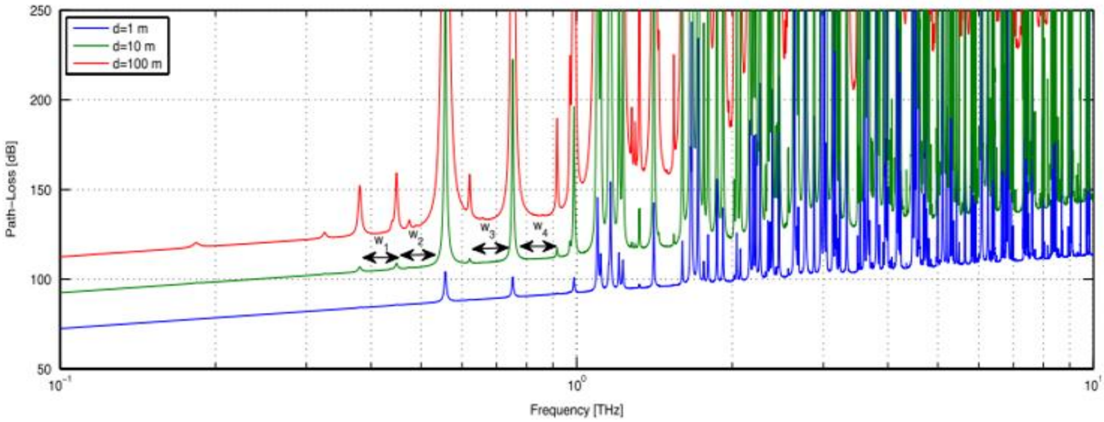

Figure 16. *Path loss in the THz band for different transmission distances [4]*

Besides from the path loss, the molecular loss is also taken into account in this model. As it is illustrated, the molecular loss is unique in terahertz band because of high frequency of molecular vibration.

The molecular absorption loss [6] can be obtained using the below formula:

$$H_{absorb}(f,d) = \exp(-\frac{1}{2}k_0(f)d) \tag{3.4}$$

The same with spread loss, f represents the frequency of the band, d is distance from the node to the receiver, k is medium absorption coefficient, it is a key parameter in calculating molecular loss. Medium absorption coefficient is crucial in calculating absorption loss. It is defined by the material itself.

The absorption coefficient can be calculated in this way:

$$k_0(f) = \sum \frac{p}{p_0} \cdot \frac{T_0}{T} . M^i \delta^i(f) \tag{3.3}$$

In this formula, p is the Kelvin system pressure, p0 is the reference pressure, is the temperatures at standard pressure, Q stands for the number of molecules per volume unit of gas I and Qi represents the absorption cross-section of gas.

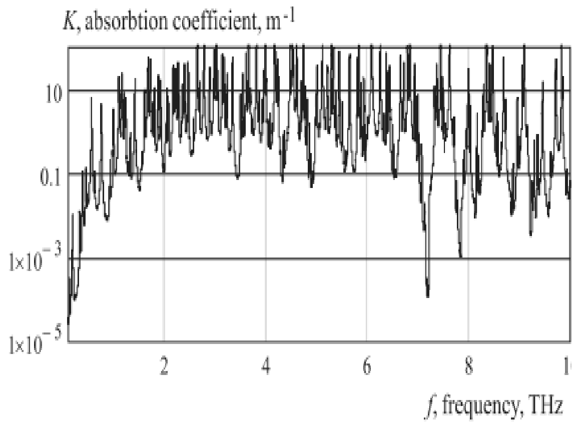

Figure 17. *Absorption coefficient [7]*

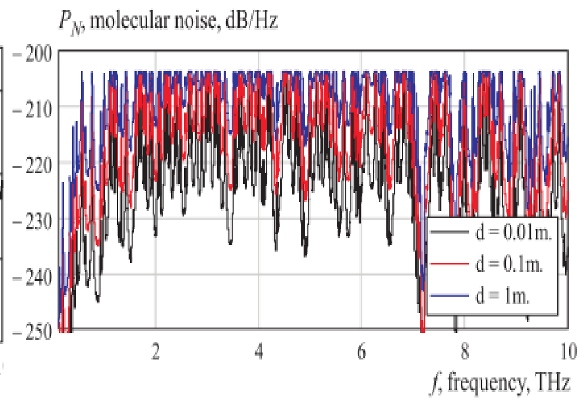

Figure 18*. Molecular loss when distance changes [7]*

After obtaining the absorption coefficient, we can look into the molecular loss of the system. As stated in Figure 18.

Given a distance, the received power from this node to the center receiver is calculated. The noise from the transmitter to the center is also defined with the given distance. Regarding to the interference in this model, we calculate it in this way:

The receiver in the center is also the center of the new circle, the distance d is the radius of the circle. The environment has N nodes following Poisson Point Process. The nodes falling inside of the circle with receiver as center and d as radius are considered as interference. Using the same method of calculating the received power of signal of interest, we can get the single interference from a single node. The final interference is the overall interference from all the nodes inside of the circle.

The received power of one node will be achieved like this:

Script of Received power from a single node script:

```
Y = X_.*10.^(-pathLossDB/20);
S_Y=1./fs*L.*(Y(:,1:NFFT/2+1).*conj(Y(:,1:NFFT/2+1)))*tma
x/real_t*2;
Power_transmited = sum(S_X(1,:))*f(2);
Power_received = sum(S_Y(1,:))*f(2);
```

3.3.2 Signal Interference versus Noise Ratio (SINR) versus lambda

The SINR value is dependent on the distance from the transmitter to the receiver. Besides the distribution of nodes also affect the value of SINR. To calculate Signal Interference versus Noise Ratio, the following formula:

$\mathrm{SINR} = \mathrm{Signal}/(\mathrm{Interference} + \mathrm{Noise})$ has been used. However, with different distance and different nodes distribution parameter lambda, SINR value changes.

Firstly, we calculate the SINR value when the distance from the transmitter to the receiver is defined while the nodes distribution parameter lambda changes.

The value of signal of interest and interference is dependent on the lambda given in Poisson Point Process. In this paper we are going to take a direct look at the differences when the value of variance is changed in Poisson Point Process. If the variance is changed in Poisson Point Process, the numbers of nodes falling into a certain region will be changed. By this means, we calculate the relationship between SINR and the changing of variance lambda.

As mentioned in chapter 3.2, the power from a single node will be calculated. The interference to the power can also be achieved in the same way: find the nodes inside of the defined circle and then add them together. It will be the total sum of interference.

When the distance from the node to the receiver is smaller than d:

```
Power_interference = Power_interference + Power_received;
```

The overall interference will be summed up:

```
Noise_overall = Noise_overall + PowerN1;
```

After received the noise and interference the SINR can be calculated:

```
SINR=Receivedpower/(Power_interfer-
ence+PowerN1+Noise_overall);
```

SINR in decibel:

```
SINR_DB = 10*log10(SINR);
```

3.4 Channel capacity versus distance

As stated in the previous chapter, change the value of variance (nodes density) the value of SINR will be changed. Same reason, when the distance to the receiver is changed, the value of SINR is changed as well. The received power of the signal of interest is changed when the distance is different. Meanwhile the nodes which are considered as interferences are also changed, not only because of the distance, but also because of the number of nodes affecting the receiver is also changed. When applying Shannon Capacity, with a given bandwidth, the value of channel capacity is related to the value of SINR.

Afterwards, we took a closer look at the module used in terahertz band. This scheme is useful in analyzing access methods. This method is called TS-OOK (Time Spread On-Off Keying) aiming at communications in between terahertz band. This mechanism is a scheme based on pulse. Channel capacity--upper bound of band throughput is not only related to the distance d to the receiver but also related to the scheme selected. In this paper, we focused on a simple On-off keying modulation--TS-OOK.

This method is based on femtosecond-long duration Gaussian pulse. On-off Keying (OOK) is the simplest amplitude shift keying (ASK). As simple as possible, this On-off Keying represents the digital signal as the presence or absence of a carrier wave. A stochastic model was produced for the noise in this terahertz band. We used this noise model to calculate the channel capacity and SINR.

In this module, logical “1” is represented by a femtosecond-long Gaussian pulse. Logical “0” is represented by silence for the same time duration t. Because of the characteristics of terahertz band, it is not able to take control of the received pulse, this OOK module is introduced [5]. Between two transmissions, the time duration is much longer than the duration of the Gaussian pulse t. The transmission of OOK can be expressed in the following figure:

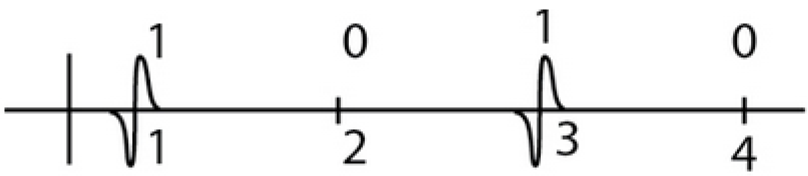

Figure 19. *Transmission of TS-OOK [5]*

As we can see from the figure, the duration of two signals 1 and 3 is much longer than the duration of a pulse. The function of it in time domain can be expressed in the following formula:

$$S_T^{\mu} = \sum_{m=1}^{M} A_M^{\mu} p(t - kTs - \tau^{\mu}) \tag{3.5}$$

As the fact that the time between two different transmissions is much longer compared to the pulse duration, transmitters can emit signal of interest without interfering with one another as there will be no collisions between the signals. The collision between silences does no harm to the signal overall. In other words, different Nano-transmitters can use the same channel simultaneously [5].

Before we discuss the value of channel capacity, we introduce a concept which will be useful in analyzing the trend of capacity: Cumulative Distribution Function, also known as CDF. If the density function of a given parameter is p(x), the Cumulative Distribution Function (CDF) of parameter x is defined as

$$P(x) = \int_{-\infty}^{t} p(t)dt \tag{3.6}$$

The function P(x) is increasing. From the definition of Cumulative Distribution Function, the following two characteristics are defined:

- The probability of the value less than x is known when x is given.
- With the value less than x the proportion of population is defined.

CDF is applied in this paper in the following way: by analyzing the trend of the changing of CDF we will know the distribution of channel capacity.

The maximum rate of information of a channel is known as Channel Capacity. In this paper we use Shannon Capacity to calculate the capacity of a given channel:

$C = B*log2(1 + SINR)$

In which B is the bandwidth of the channel, SINR is the Signal Interference versus Noise Ratio. C is the channel capacity. The value of B is given as 0.4 THz.

Script of Shannon capacity calculation:

```
B = 1.0/sqrt(2)*(max(f)); % Bandwidth calculation, -3db
Shannon_capacity = B*log2(1+SINR);
```

4. RESULTS AND DISCUSSION

Different from multiple ways for calculating and estimating terahertz channel capacity, we use a method to calculate the relative channel capacity of a given terahertz band. In this system, by changing the units of metric the corresponding channel parameters will be calculated. Because of the characteristics of terahertz band, the absorption loss, propagation loss and noise should all be taken into account. In this section we will first have a brief conclusion about the important concepts explained in the previous chapter and then analyse the results CDF of channel capacity and SINR we received from this system.

4.1 Brief theory conclusion

Channel capacity is the maximum data transferring rate in a given bandwidth. In this chapter we will validate our numeric results with the designed model in terahertz band. After that, we will analyze our results of channel capacity with multiple distances and multiple lambda values (nodes per square meters).

In this paper, we use relative distance values to calculate SINR value and channel capacity. No specific value is given to the distance so that the distance will apply to different needs. Researchers can replace the relative distance values with the absolute values needed to achieve the corresponding results. As a result, we give a more general comparison with relative values.

Due to the properties of Poisson Point Process, the distribution of nodes of interest in real will be different every time after running the simulation. This will result in differences of SINR and channel capacity values. To get a more objective results and ensure the accuracy of results, multiple times of experiments are performed. After executing the test for more than 500 hundred times, we calculated the average value of SINR for analyzing. Based on the Shannon Theory, the channel capacity is calculated once the SINR value is obtained.

The results and analyze of this thesis will be divided into two parts: one part to analyze CDF of SINR, the other analyze channel capacity. Because the CDF of SINR is not continuous resulting from this model, in the second part we will analyze the imperfections of this simulation model. Based on the current research results, factors can be improved in the future in the related field will be discussed.

We compare the difference of CDF of SINR when the distances are different. By changing the parameters of Poisson Point Process the distribution of nodes of interest are also changed. On one hand, it is one parameter of the two that we use to compare the channel properties. In this case we change the distance from the transmitter to the receiver but change the Poisson Point Process distribution parameter lambda. On the other hand, lambda value which represents the node distribution directly will be changed while the distance of signal of interest to the receiver keeps still. In this setting, we got a set of different results from variable lambda values with a certain distance.

4.2 Analysis of numerical results

Based on the variants the system simulation was run. As a result, we got the CDF of SINR, the CDF of channel capacity and the CDF of SINR in decibel (DB). In the coming content, we will analyze the trend of the received results to see the impact of distance to receiver over SINR and channel capacity and also the impact of changing of density of nodes on them.

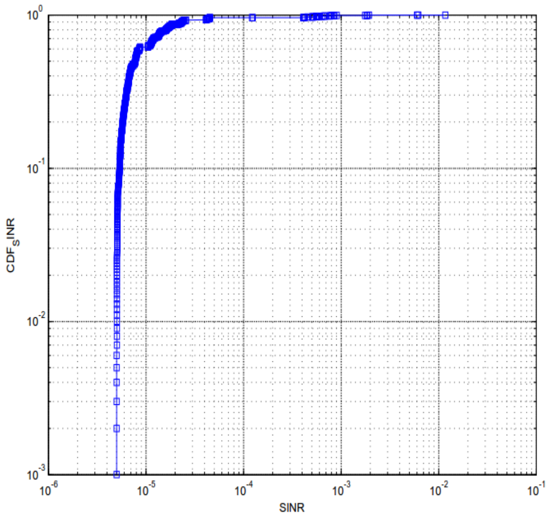

Figure 20. *CDF of SINR when the distance d = 4*

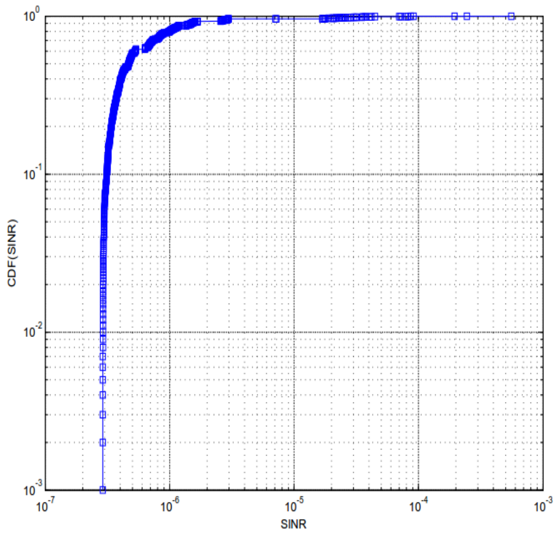

Figure 21. *CDF of SINR when the distance d = 10*

As we can see from the previous two graphs: when the distance to the receiver is 4, the value of SINR lies between 10^{-6} and 10^{-5}. When the distance to the receiver is 10, the value of SINR lies between 10^{-7} and 10^{-6}. Which means with the distance increasing from 4 to 10, the SINR value decreased. It further indicates that if the distance from the transmitter to the receiver increases, the impact of the signal of interest decreases.

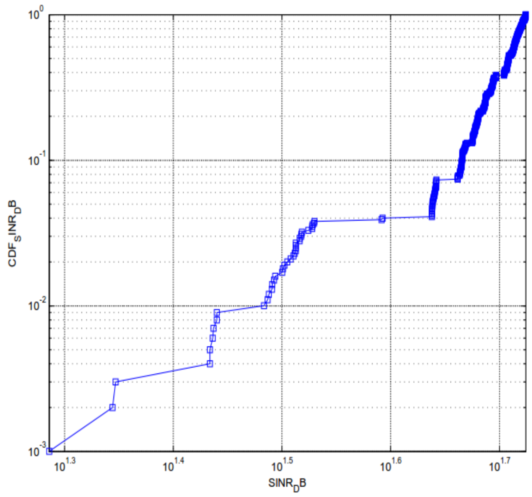

Figure 22. *CDF of SINR in decibel (DB) when the distance to the receiver d = 4*

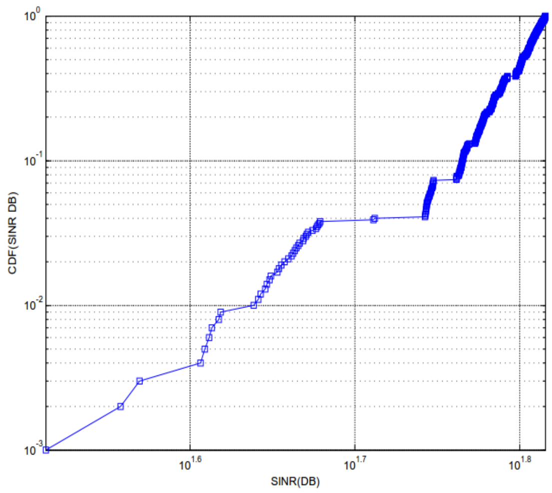

Figure 23. *CDF of SINR in decibel (DB) when the distance to the receiver d = 10*

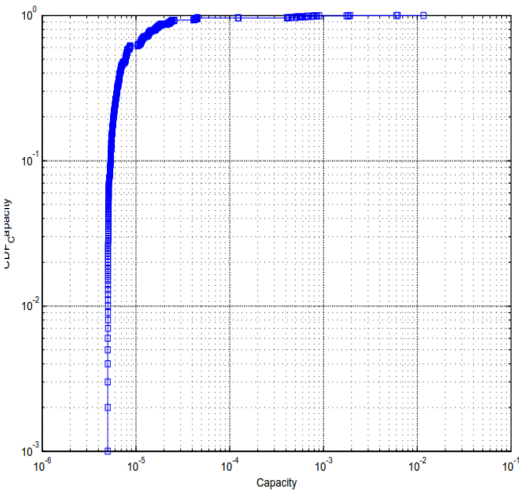

Figure 24. *CDF of Channel Capacity when the distance to the receiver d =4*

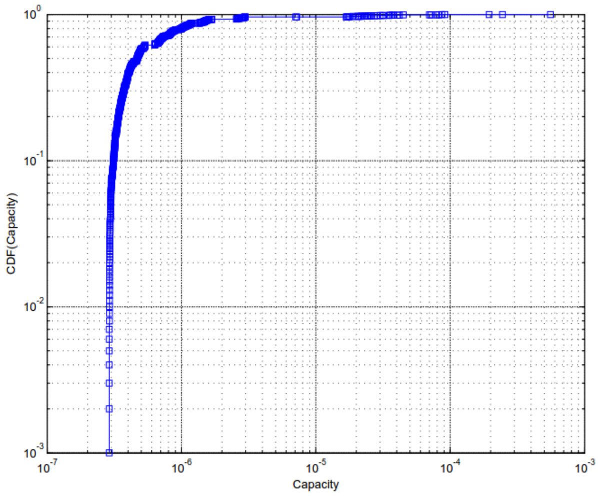

Figure 25. *CDF of Channel Capacity when the distance to the receiver d = 10*

When the distance to the receiver is 4, the value of channel capacity lies between 10^{-6} and 10^{-5}. When the distance to the receiver is 10, the value of channel capacity lies between 10^{-7} and 10^{-6}. Which means with the distance increasing from 4 to 10, the channel capacity decreased dramatically. It further indicates that if the distance from the transmitter to the receiver increases, the impact of the signal of interest decreases.

This result is in accordance with the basic assumption we had before. In the coming context we are going to present numerical results when the lambda value is defined, and distance to receiver is changed, the final SINR and channel capacity results we got.

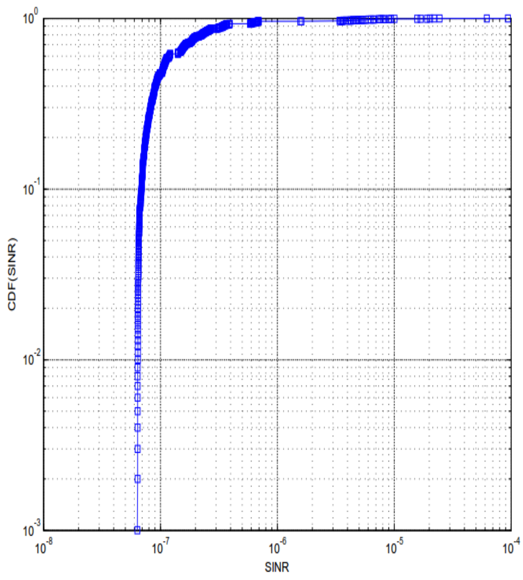

Figure 26. CDF of SINR when the distance to the receiver d = 16

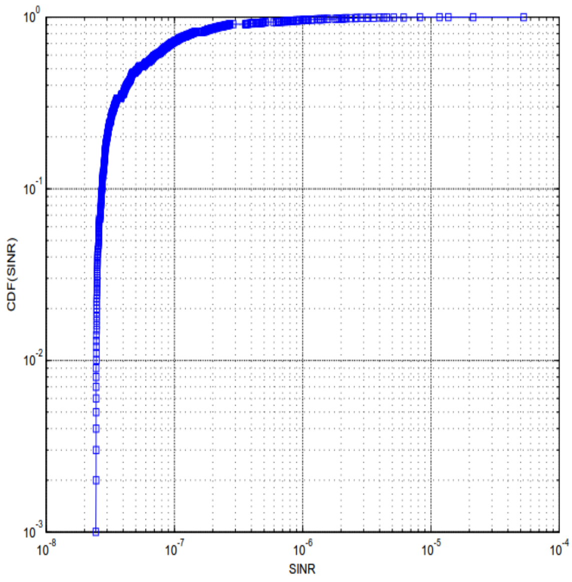

Figure 27. CDF of SINR when the distance to the receiver d = 22

When the distance to the receiver is 16, the value of SINR lies between 10^{-8} and 10^{-7}. When the distance to the receiver is 22, the value of SINR lies also between 10^{-8} and 10^{-7}. But the SINR value when distance is 16 is larger than which when distance is 22. But compared with the change when distance is increased from 4 to 10 the decreased rate is smaller.

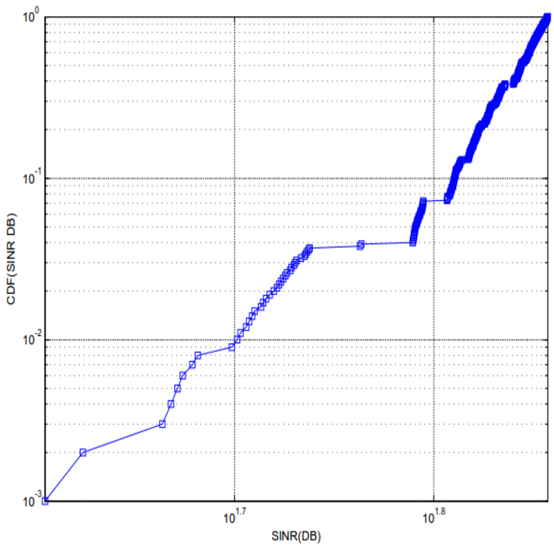

Figure 28. CDF of SINR in decibel (DB) when the distance to the receiver d = 16

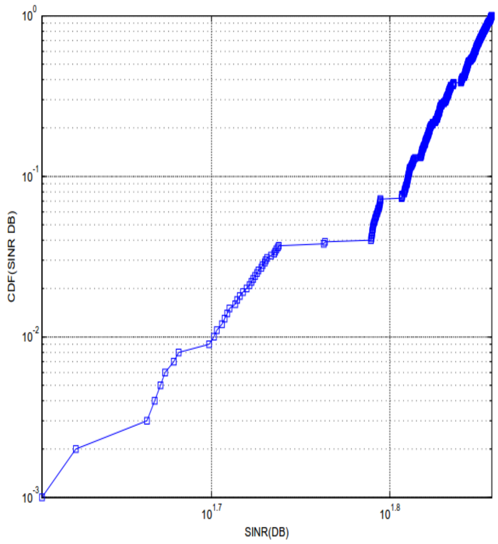

Figure 29. CDF of SINR in decibel (DB) when the distance to the receiver d = 22

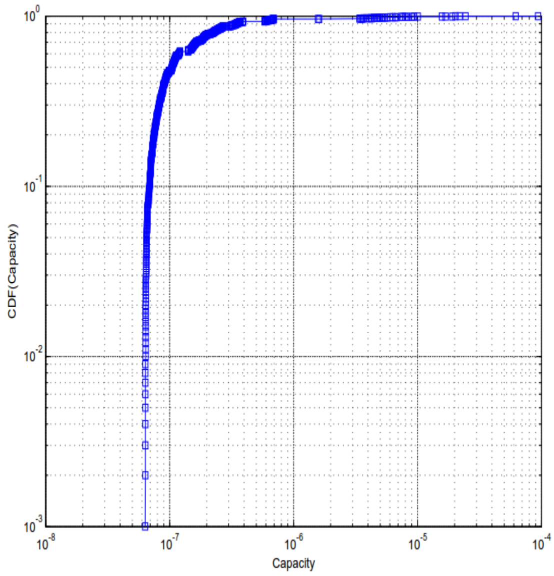

Figure 30*. CDF of Channel Capacity when the distance to the receiver d = 16*

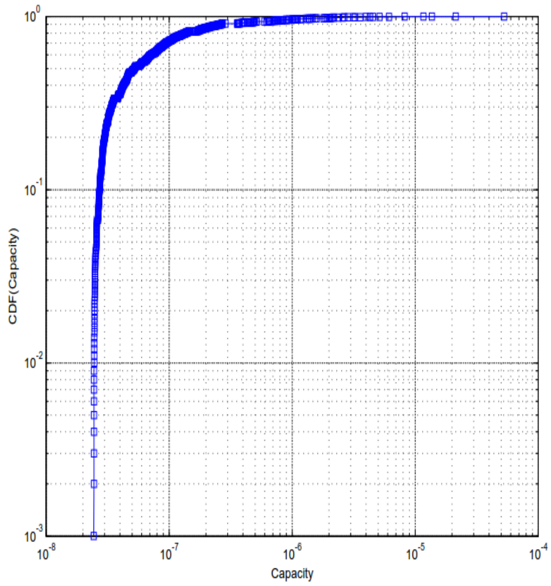

Figure 31. *CDF of Channel Capacity when the distance to the receiver d = 22*

When the distance to the receiver is 16, the value of channel capacity lies between 10^{-8} and 10^{-7}. When the distance to the receiver is 10, the value of SINR lies between 10^{-8} and 10^{-7}. Which means with the distance increasing from 16 to 22, the SINR value decreased. It further indicates that if the distance from the transmitter to the receiver increases, the impact of the signal of interest decreases.

First of all, we have the results of Signal Interference versus Noise Ratio (SINR). It allows us to validate the difference of SINR values when the relevant distances values are 4, 10, 16 and 22 respectively. The bandwidth the results based on is B = 0.4 THz. The results gave us a direct display of SINR versus distance. We can validate our theory according to the received results.

When the distance from transmitter to receiver increases the value of SINR and channel capacity decreases. What's more, SINR and channel capacity decrease much faster when the distance change is closer to the receiver. That is to say, when the distance from transmitter to receiver is increased from 4 to 10, the value of SINR and channel capacity decreases much faster than which when the distance increases from 16 to 22. Received results have proven this theory. Therefore, in terahertz band, data transmission is much faster in a short distance (for instance, 1 meter).

Received CDF of SINR: in theory, we can guess the implicit tendency of SINR versus distance. The longer the distance, the more interference nodes included. As a result, the value of SINR decreases.

In this paper, we performed analysis of SINR and channel capacity over terahertz bandwidth using the OOK model. This modulation is achieved by sending femtosecond-long pulses.

This study is based on simulation and achieved terahertz channel model. The main point of this paper is to give the absolute value analysis of SINR and channel capacity of terahertz bandwidth.

The difference of the value is based on the following assumptions:

- Different distances from transmitter and receiver while the density of nodes value is fixed
- Different lambda values of Poisson Point Process. The purpose of this research is to find out the region where the decimal of SINR is less than -100dB

The results demonstrated that communication between transmitter and receiver can be very efficient within a certain distance with a given distribution lambda. The parameters distance and lambda of Poisson Point Process affected the SINR and channel capacity in terahertz networks.

By increasing the distance to the receiver, the value of SINR decreases accordingly. By applying Shannon–Hartley theorem, the value of channel capacity also decreases as the distance d to the receiver increases. The SINR value decreased drastically when the distance doubles. It illustrated that the communication between transmitter and receiver works well if the distance is short, for example within one meter. When the distance increases after that distance the decreasing of SINR value is not that fast, but the value is relatively small already.

Abstract value of SINR and channel capacity also makes it possible for changing the metrics for future use. By this means, the future application can apply different metrics based on its own needs.

By the simulation of SINR and channel capacity of a given terahertz bandwidth, we demonstrated that the if choosing the distance to the receiver properly, the nodes or interferences outside of the circle can be neglected. Also the environment can be changed, by changing the lambda value (variance of nodes distribution), the SINR values and channel capacity related also changed. In this simulation scenario, the CDF of SINR is not continuous even after running the experiments more than 500 times. Leaning from this paper, we can change the simulation method in the future to get continuous CDF of SINR.

5. CONCLUSIONS

From the achieved results, this model indicated that terahertz network has the following features:

For terahertz network, it has a large channel capacity compared with traditional wireless networks. This feature can be utilized in multiple aspects in the future for instance uncompressed video transmission.

This developed model allows us to access CDFs and their structures which can be used to evaluate outage probability. The propagation is significantly different from lower frequencies due to the presence of molecular absorption loss which affects the transmission greatly. Due to the multiple nodes to be estimated, this simulation study is time consuming. Analytical model should be developed to assess various trade-offs and dependencies in terahertz networks.

The limitations on simulation: the simulation is time consuming. Our analytical model should be developed to assess various trade-offs and dependencies in terahertz networks.

- Complexity in reality: in this model, parameters including the distribution of nodes, interference of the system and background noise are simplified compared with the transmission in real world.
- Taking interference of other nodes and background noise into account, the simulation scenario is simplified. However, in reality the propagation is way more difficult and complex. Apart from the introduced background noise, there can be other noise in reality. To put this technology into reality it is necessary to add other factors which affect the results such as temperature and humidity. We can see from this model that short distance transmission has more advantages over long distance since in long distance transmission the channel capacity dropped dramatically. If terahertz technology is put into long distance transmission, the model needs to be optimized in a large scale.
- Due to limited communication distance and antenna systems, neighbor discovery which is used for auto-configuration of nodes and routing which is used for selecting the best routes in networks are more difficult for terahertz communication networks than traditional lower frequency networks.

The research on communication in terahertz network can be put into use widely. The study of communication in terahertz network will stimulate the applications of this technology in multiple aspects of modern society. For instance, although Internet speed has improved greatly in the past decades, the need for a higher speed is still growing. When terahertz technology is mature enough to put into market, Internet speed issue will be solved properly. Unfortunately, the distance from the transmitter to the receiver cannot be very far away in current research, more research on this technology is still in great need.

From the results received from this thesis, there are several discussions which worth being explored in the future:

- When the distance to the receiver is too close, for instance when d = 1, the interference mean value of SINR does not exist. When the distance from the transmitter to the receiver is too small, the interference of nodes can be infinitely close to the receiver. In this simulation, the value of interference can be infinite large which makes it impossible to calculate the SINR value of the system.
- If CDF exists, the CDF of mean SINR and channel capacity exists. With the increasing of distance, capacity decreases drastically.
- The second part of the research, when the distance to the receiver is fixed, the value of density of nodes (as known as lambda value in this paper) is changing. When the execution of the simulation is completed, the CDF values of SINR and channel capacity are not continuous. The results indicate the mean value CDF of SINR and channel capacity does not exist. In current simulation model, it is not suggested to execute large number of experiments while the distance from the receiver to the transmitter is fixed and change the lambda value of the environment. What's more, this experiment is time consuming under the current settings. This model conducting this assumption can be improved in the future research.

REFERENCES

[1] A. Rostami, H. R. (1965). Terahertz Technology Fundamentals and Applications

[2] Alan V. Oppenheim, G. C. (2010), Power Spectral Density. Available: MIT Open-CourseWare: http://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-011-introduction-to-communication-control-and-signal-processing-spring-2010/readings/MIT6_011S10_chap10.pdf

[3] Clegg, R. (2006), Networks II. Available: Richardclegg.org: http://www.richardclegg.org/previous/networks2/Lecture6.5_06.pdf

[4] I. F. Akyildiz, J. M. (2014), Next frontier for wireless communications. Physical Communication, pp. 23

[5] J.M. Jornet, I. A. (2014), Femtosecond-Log Pulse-Based Modulation for Terahertz Band Communi-cation in Nanonetworks, IEEE Trans, pp. 1743-1749

[6] K. Fugunaga, Y. O. Terahertz spectroscopy for art conversation, IEICE Electronics Express, 4 (8), pp. 258-260

[7] P. Boronin, V. P. (2014). Capacity and throughput analysis of nanoscale machine communication through transparency windows in the terahertz band, Nano Communication Networks, pp. 72-82

[8] Ranvier, S. (2005), Path loss models. Available: HUT Communication Laboratory: http://www.comlab.hut.fi/opetus/333/2004_2005_slides/Path_loss_models.

[9] Sherwin, M. S. (2004), Opportunities in THz, Arlington, VA: DOE-NSF-NIH Workshop.

[10] Stringer, M. Newlightsource.org. Available: New Light Source Project: http://www.newlightsource.org/events/presentations/NLS%20life%20science%20Stringer.pdf.

[11] T. May, G. Z. (2009), Passive Millimeter-Wave Imaging Technology XII, pp. 36-40

[12] UMTS. (1998), Selection procedures for the choice of radio transmission technologies of the UMTS, Nice, France: European Telecommunications Standards Institute (ETSI).

[13] T.M. Cover, J.A. Thomas, Elements of Information Theory (1991), John Wiley & Sons, Inc. Print ISBN 0-471-06259 Online ISBN 0-471-20061-1, pp. 183-185

[14] Channel Capacity and Shannon-Hartley theorem. Available: http://dsp7.ee.uct.ac.za/~nicolls/lectures/eee482f/04_chancap_2up.pdf

[15] Point process. Available: http://www.ime.unicamp.br/~nancy/Cursos/mi626/point.pdf

[16] A. Moloney, Channel Capacity. Available: http://www.electronics.dit.ie/staff/amoloney/dt008_2/dig-comms-ii-lecture-11-12.pdf

[17] J. Virtamo, Poisson process. Available: https://www.netlab.tkk.fi/opetus/s383143/kalvot/E_poisson.pdf

[18] K. Fukunaga, Y. Ogawa, S. Hayashi, I. Hosako, Terahertz spectroscopy for art conversation, IEEE Vol. 4, No. 6, pp. 259-263

[19] P. H. Siegel, Terahertz Technology, IEEE Transmission on Microwave Theory and Technologies, VOL. 50, NO. 3 (2002), pp. 910-913

[20] G. Rana, P. Deshmukh2, S.P. Duttagupta1 and S. S. Prabhu2, Design and Simulation of a Compact Terahertz Cavity for Reflection Geometry TDS Using COMSOL

[21] S. Rajaram, T. Graepel, R. Herbrich, Poisson-Networks: A Model for Structured Point Processes

[22] A. Baddeley, Spatial Point Processes and their Applications, pp. 1-20

[23] M. I. Ribeiro, Gaussian Probability Density Functions: Properties and Error Characterization (2004), pp. 2-7

[24] MIT OpenCourseWare. Available: http://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-011-introduction-to-communication-control-and-signal-processing-spring-2010/readings/MIT6_011S10_chap10.pdf

6. APPENDIX

[1] A script to calculate received power from a single node

```
%% Compute received power from a specific node
% close all;
% clear all;
%% parameters
sigma = 100e-15;
% Parameter sigma for Gaussian pulse function
t0 = 800e-15;
% t0 for Gaussian pulse function
Emax = 1e-19;
% Maximum energy

lend = 100;
%number of space distances
c = 2.997925e8;
%[m/s] speed of light
fs = 1e14;
%sample rate -- 10 times the highest frequency
ts = 1/fs;
%sample period
t = (0:1:2^16)*ts;
% Time sequence
tmax = max(t);
%for normalization purposes
L = length(t);
% the length of time vector
NFFT = 2^nextpow2(L);
% returns the smallest greater than or equal to the absolute
value of 2 powered by L
Nderiv = 1;
%% Positive going monopulse
x=1/(sqrt(2*pi)*sigma)*exp(-(t-t0).^2/(2*sigma^2)); %Gauss-
ian pulse function
% xn = x./sqrt(sum(x.^2)./fs)*sqrt(Emax); %Total energy Emax
%
% X = fft(xn,NFFT)/L; % Fourier transform of xn
% S_X = 1./fs*L.*(X(1:NFFT/2+1).*conj(X(1:NFFT/2+1)));
% Psd of X
```

```
%% Perform several derivaties
for i=1:Nderiv
    x(1:L-1) = diff(x)./diff(t);
    x(L) = 0;
    xn = x./sqrt(sum(x.^2)./fs)*sqrt(Emax);
    X = fft(xn,NFFT)/L;
    S_X = 1./fs*L.*(X(1:NFFT/2+1).*conj(X(1:NFFT/2+1)));
end

real_t = sum(abs(xn)>0.01*max(xn))*t(2);
% This is to see the pulse power
f = fs/2*linspace(0,1,NFFT/2+1);
% Create frequency vector, which length is NFFT/2+1, line-
arly spaced (0,fs/2)

%% Channel
% Load Parameters
load mol_abs.mat % molecular parameters
% Molecular Absorption Loss
tau = sum(kvt(1:8,:),1);
% Absorption coefficient [cm^-1]
absLossDBM = 10*tau*1e2*log10(exp(1));
% Absorption Loss [dB m^-1]
absLossDB = (Dis)'*absLossDBM;
% Absorption Loss (dB)

% Spreading Loss
% Previously I used the frequency dependent term for the
effective area
%SpreadLossDB=20*log10(4*pi*d')*ones(1,length(f))
%+ones(1,length(d))'*20*log10(f./c);

% Effective area of the receiving antenna
[maxx,f0] = max(X(1:NFFT/2+1)); % maxx is the highest value
of X, and f0 is the index of maxx
spreadLossDB=20*log10(4*pi*Dis')*ones(1,length(f))
+ones(1,length(Dis))'*20*log10(f(f0)*ones(size(f))./c);
%Calculating DB of spreadloss

% Total Path Loss
pathLossDB = absLossDB+spreadLossDB;
```

```
% Path loss equals to DB of absortion loss plus DB of spread-
loss
pathLossDB(:,1) = 0;
% Path-loss at 0 Hz is always 0
pathLossDB = pathLossDB.*(pathLossDB>=0);
% Path-loss expression only valid in the far field, always
positive

%% Signals spectrum
X_ = ones(1,length(Dis))'*X(1:length(f));
% Power spectral density for X, transmission signal
S_X=1./fs*L.*(X_(:,1:NFFT/2+1).*conj(X_(:,1:NFFT/2+1)))*tma
x/real_t*2;
%Power spectral density for Y, received signal
Y = X_.*10.^(-pathLossDB/20);
S_Y=1./fs*L.*(Y(:,1:NFFT/2+1).*conj(Y(:,1:NFFT/2+1)))*tmax/
real_t*2;
%Enery and Power -> JUST TO VERIFY I'M DOING EVERYTHING
CORRECTLY
Power_transmited = sum(S_X(1,:))*f(2);
% transmitting power
Power_received = sum(S_Y(1,:))*f(2);
% received power
%snr= 10*log(Power2/(PowerN0 + PowerN1));
```

[2] To calculate the SINR of the system

```
% clear all;
% close all;
% Parameters
% lambda = 0.03;
% Points intensity points/meter^2
X_length= 50;
% Length of the quare
Mean_points = X_length^2*lambda;
% Mean value of the poisson points process
N = X_length^2*lambda;
% Number of points
Power_interference = 0;
% The overall power receiver received
Noise_overall = 0;
distance_all = 2:2:24;
lambda_all = [0.01,0.04,0.07,0.1];
```

```
% Calculat the received power and noise from the signal node.
 d = 25;
 Dis = d;
% received_power;
% Calculate the received power from this node to center
% noise_distance;
% Calculate the noise from the transmitter to the center
% Receivedpower = Power_received;
%fileID = fopen('exp.txt','w');
%Openn a txt file name 'exp.txt'

% Calculate the time needed for N nodes
for d = 2:2:24
received_power;
% Calculate the received power from this node to center
noise_distance;
% Calculate the noise from the transmitter to the center
Receivedpower = Power_received;
count = 1;
% generate N points
%for i = 1:N
while count <= N
    Points_N = poissrnd(Mean_points,[1,2]);
    %The coordinates of the node are stored in a 1*2 matrix
    Points_N(1) = unifrnd(0,X_length);
    %Get the uniform distribution value of X coordinate
    Points_N(2) = unifrnd(0,X_length);
    %Get the uniform distribution value of Y coordinate
    Dis = sqrt((Points_N(1)-X_length/2).^2
    + (Points_N(2)-X_length/2).^2);
    % Calculate the distance

    If(Dis>=1)
% between the node to the center
    count = count + 1;
    received_power;
% Calculate the received power from this node to center
    noise_distance;
% Calculate the noise from the this to the center
     if Dis<=d
        Power_interference = Power_interference
                                  + Power_received;
% Overall interference
```

```
         Noise_overall = Noise_overall + PowerN1;
% Overall noise
      end
    end
end

%% SINR Calculation
SINR=Receivedpower/(Power_interference+PowerN1+Noise_over-
all);
% SINR Calculation
SINR_DB = 10*log10(SINR);
% SINR in decibel

%% Shannon capacity calculation
B = 1.0/sqrt(2)*(max(f));
% Bandwidth calculation, -3db
Shannon_capacity = B*log2(1+SINR);
% Print SINR with relevant lambda and distance
fprintf(fileID,'lambda = %d,radius = %d, SINR = %d , Capacity
= %d. \n',lambda,d, SINR_DB,Shannon_capacity );
SINR_index = SINR_index + 1;
SINR_All(SINR_index) = SINR;
%Mean_all_experiments(SINR_index)=Mean_all_experi-
ments(SINR_index) + SINR_All(SINR_index);
end;
%fclose(fileID);
%toc
```

[3] Multipath lambda values

```
SINR_index = 0;
SINR_All = zeros(1,48);
for lambda = 0.01:0.03:0.1
    Environmenttest;
End
```